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Accounting for the Local Wave and Morphodynamic Processes in Coastal Hydraulic Engineering

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Abstract

Purpose. Estimates of wave parameters in the coastal waters are of great practical importance for designing and operating coastal infrastructure facilities. On the example of the Saki bay-bar region (Western Crimea), the experience of studying the wave and morphodynamic processes in the coastal zone is presented being applied to the tasks of designing and building protective hydraulic structures.

Methods and Results. Mathematical modeling of the wave and morphodynamic processes in the area under study was done using the following: spectral model of the wind waves SWAN, hydrodynamic model SWASH, complex morphodynamic model XBeach and integral model of the coastal zone evolution GenCade. The wave regime was analyzed using the 41-year time series (1979–2019) of wave parameters resulted from the retrospective calculations of wind waves based on the SWAN model and the ERA atmospheric reanalysis data. The operational and extreme characteristics of wind waves were obtained. The spatial structure of the wave fields for different types of wind effects was modeled. The most intense waves are shown to occur during the southwest wind. The height and length of wave run-up on the coast and the coastal zone profile deformations for the storms of different durations were estimated. The values of the total annual along-coastal sediment flow in the design area were obtained for 1979–2019. In 70% of the cases, the sediment flow was established to be directed towards the Evpatoriya coast.

Conclusions. The studies have shown that neglecting scientifically based recommendations when designing coastal infrastructure facilities can lead both to disruption of the existing system of the coastal zone natural formation, and to significant negative consequences for the coastline of almost 10 km length. These consequences can be manifested in a reduction of the beach zone width, a decrease in elevation marks, and replacement of sand with the pebble-gravel fractions in some areas that worsen recreational features of the beaches. Having been analyzed and taken into account, the planned location of the base of the enclosing wall shows that in some parts, the embankment wall can be possibly washed away and damaged. These conclusions were confirmed in practice already during the facility construction. Based on the results of the performed study, the constructions contributing significantly to the changes in the coastal zone morphodynamics were recommended for exclusion from the project.

Keywords: coastal zone, anthropogenic impact, wave regime, morphodynamics, Crimea, Sakskoe Lake, bay-bar, mathematical modeling, SWAN, SWASH, XBeach, GenCade

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Introduction

The southern (SCC) and the western coasts of the Crimean Peninsula are the two main resort areas, each of which receives about 40% of the total flow of vacationers. The possibilities of expanding recreational areas in the South

Caucasus are practically exhausted. In that case, Western Crimea can potentially significantly increase them, which has resulted in the creation of a number of projects for the further development of this region. One of these projects is called "Construction of a pedestrian embankment along Morskaya Street, Republic of Crimea, Saki", which, unfortunately, provides for serious interference in the natural processes of the coastal zone of the Sakskoe Lake bay-bar, previously already subjected to negative anthropogenic impact.

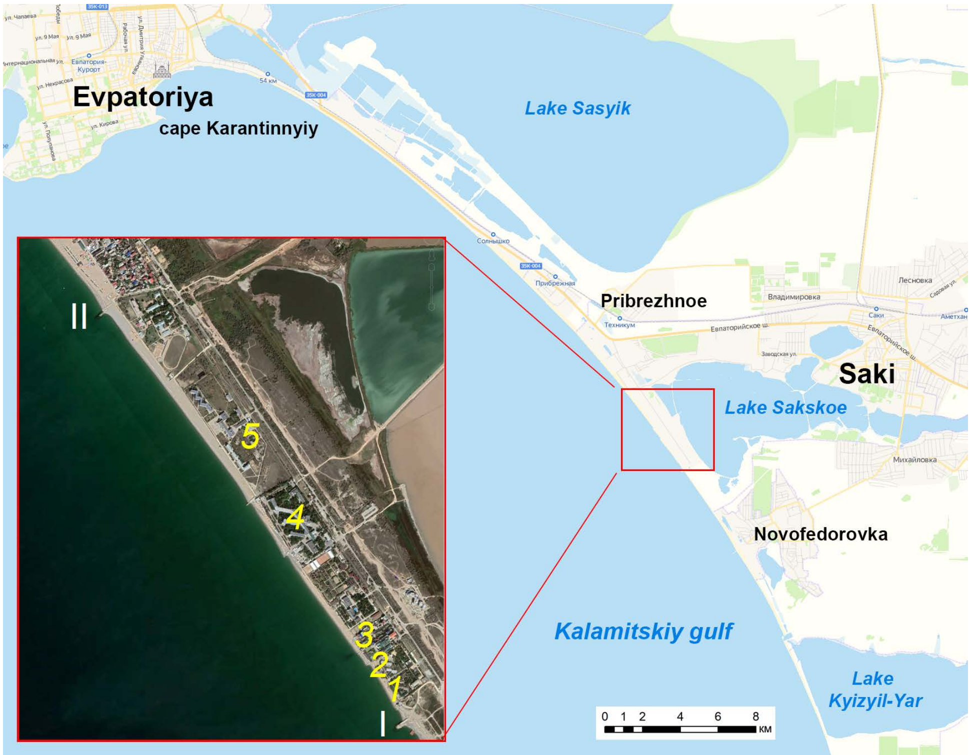
It is quite obvious that when implementing such projects, it is necessary to take into account the peculiarities of the natural conditions of a particular coast area and the previously gained experience of its economic development. Unfortunately, this was not done by the designers, despite repeated warnings from the scientific organizations of Crimea. Due to the apparent negative impact on the coastal zone, construction was suspended, and the project was sent for revision.

The purpose of this work is to analyze the anthropogenic impact on the coastal zone in the area of the Sakskoe Lake bay-bar, obtaining characteristics of the wave regime and morphodynamics based on field data and modern mathematical modeling methods.

Retrospective analysis of the reaction of the design site coastal zone to anthropogenic impacts

The main and oldest resorts of Western Crimea are the cities of Evpatoriya and Saki, located on the shores of the Kalamitskiy gulf, which stretches in an arc of 60 km from Evpatoriysky Cape to Cape Lukull (Fig. 1). The bay shores form an abrasive-accumulative pair. The southern half is represented by an abrasive coast with a steep cliff (up to 15 m high), composed of red-brown clays, with the inclusion of horizons of pebble conglomerates. The destruction of cliffs, along with bottom abrasion, is currently the main source of sediment in the coastal zone [1]. The mean rate of cliff retreat is 0.5–1 m/year [2]. Sediments of the southern part feed the northern half of the bay, the coast of which is a part of a single accumulative formation from Karantinnyiy Cape to Kyizyil-Yar Lake. Previously, alluvium from rivers accounted for a significant share of the beaches' feed, but with their regulation in the 70s of the past century, it began to play an insignificant role in the balance of sediments.

The Sakskoe Lake bay-bar, composed of sand and pebble material, is a closing accumulative coastal form. Such forms are created as a result of transverse displacement and ejection of sediment from the bottom during along-shore sediment migrations in places where sediment flow is inhibited or under the combined action of these processes and are a relatively stable element of the coastal zone. At the same time, over the past 90 years, the bay-bar has undergone a number of anthropogenic impacts, as a result of which the coastline has retreated significantly, and the beaches have experienced degradation.



F i g. 1. Schematic map of the Kalamitskiy gulf northern part. The inset shows the location of groins No. 1 and 2 (indicated by Roman numerals I and II); yellow numbers denote: children center "Art-Quest" – *1*; sanatorium "Yurmino" – *2*; recreation center "Uyut" – *3*; sanatorium "Poltava" – *4*; boarding house "Sail" – *5*

Back in the mid–20th century, there were full-profile beaches with a dune landscape, the bay-bar height above sea level was 1.5–5 m [3]. The immediate reason for the reduction of beaches was the extraction of sand from them, which began in the 30s during the construction of DneproGES (the sand was of very high quality). Then it was localized mainly near Pribrezhnoe village. Production reached its maximum in the 50s, when the intensive development of Pribrezhnoe sand-gravel mixture deposit, which included the bay-bars of Sasyik and Sakskoe lakes, was underway. Sand was used for construction not only in Crimea, it was exported by rail and by sea to Odessa and other ports. The embankments separating the pits from the sea became narrow and curved towards the pit, while a reduction in the width of the beaches took place. The maximum retreat of the coastline was ~ 120 m. In February–March 1953, the municipal commission came to the conclusion that no further sand and gravel development could be allowed on either the Sasyik or Sakskaya bay-bars. Nevertheless, the extraction continued for several more years.

At that time, on the Sakskoe Lake bay-bar the buildings that would be threatened by the retreat of the shore were practically absent. However, due to the real danger of the bay-bar breakthrough by the sea, changes in the brine salinity in the lake with therapeutic waters, and the loss of the therapeutic properties of the Saki resort mud, the pits on land were closed.

At the same time, the extraction of sand by refilling it from the bottom of the sea was continued, while the situation worsened, the long-shore sediment flow was almost completely intercepted, as a result of which the coast began to retreat intensively. At the same time, a decrease in beaches in Evpatoriya took place, and in the early 60s sand mining was completely stopped. The total volume of extracted sand [1] was estimated at ~ 15 million m^3. The railway line brought here for the removal of sand, subsequently modernized, has been preserved in places to this day. Instead of sand dunes located here, salt lakes and swampy areas (droughts) were formed at the site of sand mining, partially subsequently filled in and built up.

After the closure of the sand pits until the early 80s of the past century, the coast gradually stabilized. However, then it began to erode rapidly, and between 1983–2006 on the Sakskaya bay-bar, it retreated by 18–33 m. The immediate cause for this was the construction in 1982 in the area of Novofedorovka village of a protective structure for the water intake of NITKA facility. It is an L-shaped solid reinforced concrete pier extended into the sea from the south side, and a rectilinear pier from the north side. The structure intercepted a long-shore sediment flow coming from the south. As a result, sediments began to accumulate to the south of the structure, and the coastline over time extended to its entire length – 80 m. To the north of the water intake, an intensive retreat of the coast began, and the classic phenomenon of low-level erosion was observed, as a result of which a significant part of the coast was affected.

Thus, in the area of Art-Kvest Children’s Center (shown by number *1* in the inset of Fig. 1) the coast abruptly retreated between 1984–1985 by 10 m. In 1989, a vertical wall was built as protection, but by 1999 it collapsed, eventually the shore retreated here by 29 m.

Between 1983–2006, in the area from Art-Kvest Children’s Center to the *Sail* Boarding House (shown by number *5* in the inset of Fig. 1) the mean value of the shore retreat was 18 m. Other areas of this coast were also affected. By 2011, on the territory of the “Yurmino” Sanatorium and the Uyut Recreation Center (numbers *2* and *3* in the inset of Fig. 1) the coastline retreated by 24–33 m compared to 1983. As a result, by the end of the 80s of the past century, almost the entire site of the current design and construction was recognized as an emergency. In an attempt to prevent the destruction of various buildings caught in the surf zone, sketched transverse structures holding the beach, protective sketches made of various materials, walls with wave-extinguishing chambers made of slotted plates, and walls made of polymer materials were used on the territory of individual health resorts. For the winter period, sand shafts in combination with trenches were erected as barriers to waves. Although these measures did not solve the problem as a whole, they still

[1] Shuiskyi, Yu.D., Plotnikova, K.I. and Vykhovanets, H.V., 1982. [Coastal Zone Dynamics in the Areas of Deposits of Solid Minerals]. In: V. I. Melnik, ed., 1982. [*Basic Problems of Geology, Exploration and Extraction of Minerals of the World Ocean Shelf Zone. Materials of the Rep. Conf.*]. Kiev: Naukova Dumka, 1982. pp. 119-127 (in Russian).

made it possible to protect the territories adjacent to the beach to some extent during the storm season. However, local protection of the coast led to the erosion of other areas.

As an example, we will describe the consequences of the construction in 2008 on the territory of the "Poltava" Sanatorium (shown by number *4* in the inset of Fig. 1) of a complex of coastal protection structures consisting of a vertical wall and two gravity groins limiting the main beach. As a result of the groin construction, the mean width of the beach began to increase and quickly stabilized at 30–35 m. Artificial replenishment of the beach material volumes was not carried out. The filling of the interdental space of the beach and some increase in its width to the south occurred as a result of the interception of a part of the long-shore sediment flow directed from the south to the north, which led to intensive bottom erosion.

In the first months after the completion of construction on the territory adjacent to the "Poltava" Sanatorium from the north, the beach width was reduced to 8–10 m, which caused the destruction of the coastal ledge in its rear by wind waves. By the end of 2011, the shore here retreated 25 m from its original position. The zone of intensive erosion of the coastal slope was most clearly traced at a distance of ~ 250 m north of the northern groins. On this site, there was complete destruction of a strip of shrubby plantings and a promenade. At the same time, there was a washout and destruction of the restrictive stone wall of the beach. Southward of groins, an increase and stabilization of the beach width at a length of ~ 800 m was observed. Thus, it was clearly shown that, along with seasonal and interannual variability of the directions of the longshore sediment flow, its predominant direction is from south to north.

In the early 2000s, there were several plans to restore the bay-bar beaches, which were not implemented. So, according to one of the projects, it was planned to fill a free artificial beach 2800 m in length.

Critical analysis of existing design considerations

The purpose of the project, developed in 2016 by Beregozashchita LLC (Krasnodar), was the construction of an embankment of 5600 m in length, as well as the expansion of the beach area in the central design area (length ~ 2400 m), where the width of the beach was 10–30 m and the embankment wall and coastal structures were exposed to wave action. Here we will not dwell on the dubious idea of building an embankment, but we will note only those decisions that relate directly to the coastal zone. The designers carried out surveys, the completeness and quality of which are controversial. The main conclusion on which the choice of the design scheme of the coastal protection structures was based was that the sediment flows at the design site are balanced on mean per year and the resulting flow is close to zero. The project determined the construction of two concrete transverse structures along the boundaries of the central section (groins No. 1 and 2, Fig. 1) of ~ 120 m in length each. In the central section, it was planned to fill the beach of 35 m in width with the replacement of existing sand-pebble fractions (0.25–10.0 mm [4]) with gravelboulders (70–80 mm), which sharply worsened the recreational properties of the beach. From the sea side, this section was planned to be protected from wave action by ten intermittent concrete breakwaters parallel to the shore. A protective embankment wall was designed to the north and south of the existing buildings of health resorts on the site of the dunes of the natural beach. It was assumed that there would be no changes in the width and height of the beach on these sites. In this regard, there was no provision for dumping of beach material and carrying out other shore protection measures in the northern and southern sections.

Despite the criticism of the design solutions voiced during the public consultations by the Marine Hydrophysical Institute (MHI) of the Russian Academy of Sciences, by the beginning of 2020, the following construction and installation works were completed: the embankment wall was built on the southern and northern sections, the root parts of the groins of 63 m (No. 1) and 42 m (No. 2) in length, the beach was filled in the area between the southern and northern groins in a volume that there is no reliable information about.

Soon after the start of the construction, the negative consequences of design decisions were revealed. In order to study the influence of the constructed sites on lithodynamics, we carried out full-scale observations of underwater and surface relief, a comparison of profiles on control gates, and a preliminary assessment of changes in the fractional composition of sediments. Based on the results obtained, it was found that partially constructed groins significantly affect the transformation of the coastal strip both above the shore horizon and at depths up to 4.0–4.5 m.

It should be noted that before the construction of groin No. 2 (2019), the structures were built in the beach active zone at the sites of recreational facilities (Art-Kvest Children's Center, the "Yurmino" Sanatorium, the Uyut Recreation Center), while the reduced width of the beach was not enough to completely extinguish wave energy. Over the 2020–2021 period, almost complete loss of the beach in these areas was noted (Fig. 2). At the same time, pebble-gravel material began to accumulate from the southern sides of groin No. 2, and the sand was washed away by waves and moved towards the open sea.

Due to a change in the granulometric composition (a decrease in the content of the sand fraction) in the area southward of groin No. 2, a decrease in elevation and a decrease in the width of the beach took place. The partially constructed groin, as well as the presence of additional obstacles in the form of remnants of the technological berm and a pontoon abandoned at the facility, blocked the sediment flow, which has a general coastal direction from south to north here. The erosion of the northern corner at groin No. 1 and the extension of the pebble beach from the southern side were also noted.

In relation to the justified concern of the owners of coastal structures for the safety of beaches, as well as in connection with the real threat of washing away the foundation of the built protective wall, the Marine Hydrophysical Institute of RAS initiated the work on the project analysis in terms of construction in the coastal zone.

F i g. 2. View of the coast in the region of the “Yurmino” sanatorium (January, 2022)

Mathematical models used

When designing hydrotechnical structures in the coastal zone, as a rule, calculation methods from regulatory documents are used. For the most part, these techniques are developed on the basis of simple analytical solutions, they use serious simplifications of the processes under consideration. In specific engineering and hydrometeorological surveys, the use of these techniques is not always possible, which often leads to the need to involve numerical models for obtaining more accurate estimates of the parameters required for the design.

A long-term experience of MHI in studying the dynamics of coastal processes has made it possible to identify a set of numerical models that enable to solve a wide range of tasks required for the design of coastal protection structures. As practice shows, a reasonable combination of regulatory techniques and numerical models can give more reliable and objective estimates of the parameters necessary for the design of hydrotechnical structures.

The set of models discussed below has been repeatedly used by MHI within the framework of scientific and technical support of hydrotechnical engineering projects in the coastal zone of Crimea. The main criteria for choosing models are openness and free distribution of source codes; comprehensive testing of models and their general recognition by the international scientific community; availability of well-developed documentation for users.

The SWAN numerical spectral model [5] is used as the main tool for modeling waves in the coastal zone, which takes into account wave generation by surface wind; wave breaking in deep water; nonlinear interaction of wave harmonics in deep and shallow water; refraction on inhomogeneities of the bottom relief; wave breaking in deep water; bottom friction and wave breaking at critical depths.

The main technological problem in modeling waves in coastal areas is the correct specification of the characteristics of waves coming from the open sea. For this purpose, unstructured grids with thickening in the coastal zone or rectangular nested grids are usually used.

In this paper, a 4-step method of nested rectangular grids was implemented: at the first step the wave fields in the entire Black Sea basin are modeled; at the second step the waves are calculated in the area including the Kalamitskiy gulf; at the third step, the wave fields in the northern part of the Kalamitskiy gulf are calculated; at the fourth step, the wave fields on the approaches to the area under study are modeled. At the second, third, and fourth steps, the parameters of wind waves at the liquid boundaries of the calculated regions are determined by interpolation of the model data obtained at the previous step. This approach makes it possible to obtain wind wave fields with different details and at different distances from the studied area.

The SWASH numerical hydrodynamic model [6] was applied to calculate wave flows and wave surge, which enables modeling in a wide range of space-time scales, taking into account refraction, diffraction and reflection of waves. The model takes into account turbulent mixing, bottom friction, wave breaking, flooding – drainage processes of the coastal zone. The SWAN wave model data can be used as boundary conditions on the sea boundary.

The solution of morphodynamic problems on the scale of the duration of individual storms or storm cycles was carried out on the basis of the XBeach complex numerical model [7], which enables simultaneous calculations of the characteristics of waves and currents, sediment transport and changes in the coastal zone relief.

Estimates of shoreline changes over several years were carried out on the basis of the GenCade integral shoreline evolution model [8], the main purpose of which is to determine interannual trends in shoreline changes with different types of coastal protection structures.

Using the above-mentioned mathematical models, it is possible to solve a fairly wide range of practical problems arising during the implementation of economic activity projects in the coastal zone, given below.

Some of the results of mathematical modeling of wave and morphodynamic processes obtained by MHI within the framework of research work on the development of recommendations for the selection of types and schemes of coastal protection structures placement on the embankment construction site in the area of the Sakskoe Lake bay-bar are given below.

Regional wind-wave climate

The first step in solving the problems of designing coastal protection structures is to obtain statistical characteristics of waves in the area under study. For this purpose, long-term series of urgent observations of waves at the nearest marine hydrometeorological stations (MHS), representative of the area under study, are usually used. For the area of the Sakskoe Lake bay-bar application of the wave observation data from Evpatoriya MHS (which were used by Beregozashchita LLC) is not entirely correct, since the MHS is located in a semi-enclosed bay and does not characterize the wave regime of the studied area.

The way out of this situation is to use the data of retrospective calculations of waves over a multi-year period. MHI has a data set of retrospective calculations of wind-wave parameters in the Black Sea over the 1979–2019 period (hereinafter referred to as the SWAN–ERA array) with a time discreteness of 1 h. The array was obtained using the SWAN model on an unstructured computational grid with condensation in the coastal zone [9]. The atmospheric forcing of the model was the data of global atmospheric reanalysis ERA-Interim and ERA5 (https://www.ecmwf.int/en/forecasts). From the SWAN-ERA array, the closest to the Sakskoe Lake bay-bar computational grid node with a depth of ~ 9 m and long-term series of wave parameters have been formed, including the significant wave height h_S, the mean wave period $\bar{\tau}$, the mean wave direction θ, and the peak wave period τ_P.

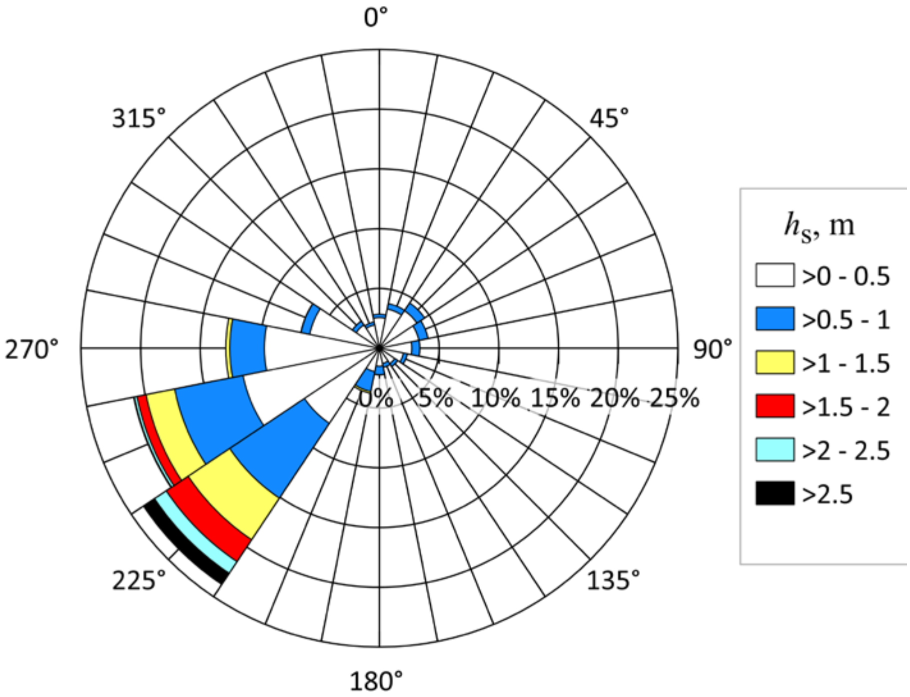
On the basis of these series, operational and extreme characteristics of the waves [2] were calculated: operational characteristics determine the background operating conditions of coastal infrastructure facilities and extreme ones – the regime of maximum loads on these facilities.

Analysis of the results of operational characteristics' calculations showed that with increasing wave height its repeatability monotonically decreases. About 70% of all h_S values do not exceed 0.5 m. Waves with $h_S \geq 1$ m height occur in 7% of cases, and the frequency of waves with $h_S \geq 2.5$ m height is less than 1%. The greatest repeatability of the mean wave periods corresponds to 2–3 s interval, in which 52% of all cases fall.

From the sea side, the south-westerly wind has the greatest frequency (6%). At the same time, the most likely direction of the waves' approach to the shore is south-west and west-south-west (Fig. 3).

The maxima of wave direction frequency correspond to the maxima of wind direction frequency and are due to the distribution of depths and refraction, under the effect of which, as they approach the shore, the wave fronts are oriented parallel to the isobaths. The distribution of wave periods in directions and gradations demonstrates that the waves with $\bar{\tau} \geq 7$ s periods approach the study area from the southwest and south-southwest, which qualitatively repeats the wave rose.

[2] Krylov, Yu.M., 1966. [*Spectral Methods to Study and Calculate Wind Waves*]. Leningrad: Gidrometeoizdat, 255 p. (in Russian).



F i g. 3. Wave rose according to the SWAN-ERA data (9 m depth)

On the basis of the available wave series, the duration of storm situations and the intensity of storms were also estimated. The condition [10] was used as a criterion for identifying storms

$$h_S \geq \overline{h_S} + 2\sigma, \tag{1}$$

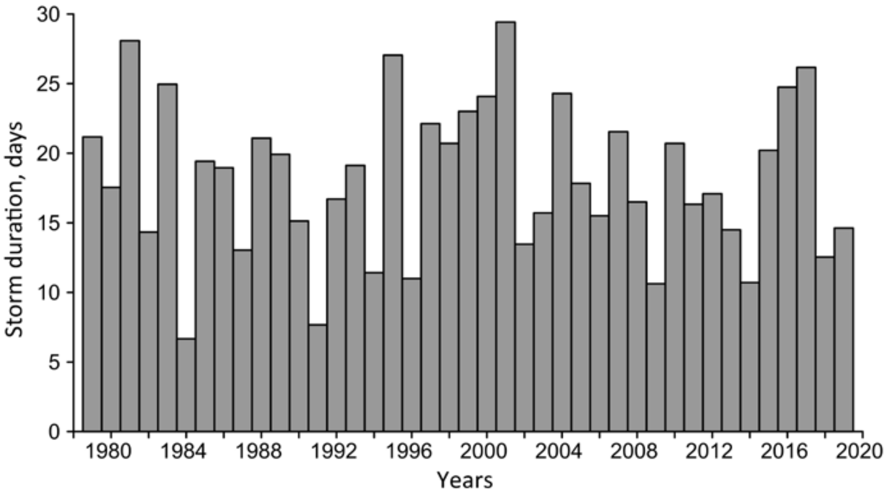
where $\overline{h_S}$ = 0.54 m is the mean annual value h_S for this series; σ = 0.50 m is h_S root-mean-square deviation of the waves from $\overline{h_S}$. Thus, the threshold value of the waves' height h_P = 1.54 m.

Fig. 4 demonstrates yearly distribution of the total duration of storm situations. As you can see, it varies between 6.7–29.4 days, and their mean value is 18.2 days. The longest storm situations occur in December – January, and the minimum duration of storms is observed in July – August (Fig. 5).

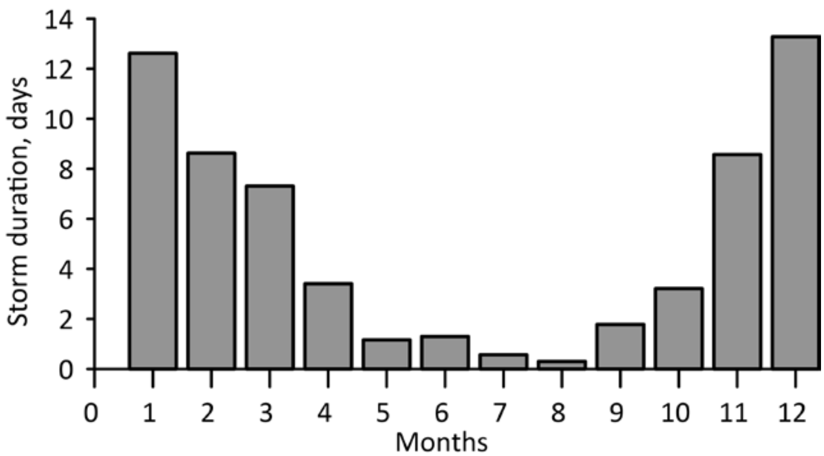
A fairly informative characteristic of the waves is the *SPI* (storm power index), calculated according to the formula from [10]:

$$SPI = h_d^2 \cdot T_d\,, \tag{2}$$

where h_d is a mean value for the storm period h_S (m); T_d is a storm duration (h). When calculating T_d and h_d, the values of h_S that satisfy the criterion (1), are used.



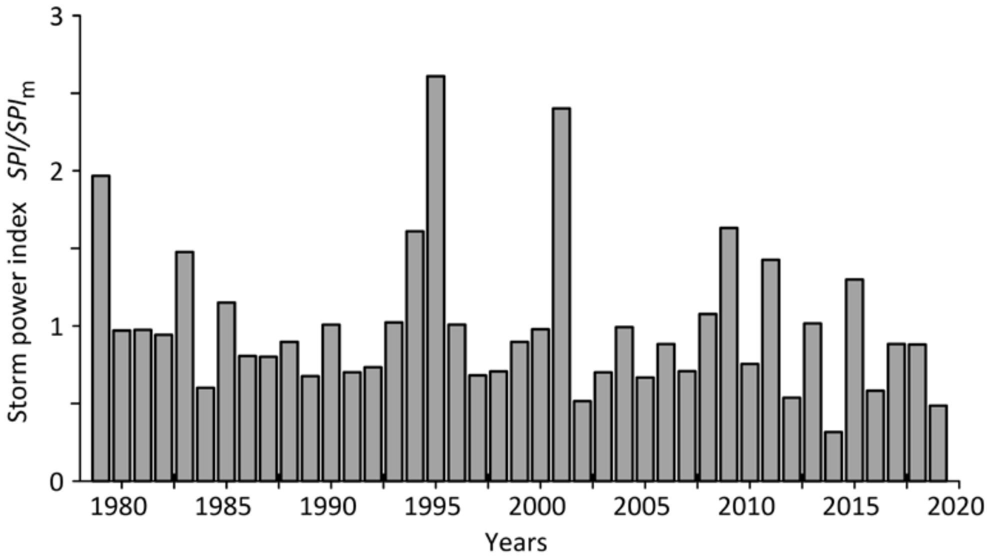
F i g. 4. Yearly distribution of the storm total durations according to the SWAN-ERA data (9 m depth)



F i g. 5. Monthly distribution of storm mean durations according to the SWAN-ERA data (9 m depth)

Figure 6 shows yearly distribution of the total *SPI* values, normalized by the mean annual value of SPI_m = 0.869·106 m^2·h. The histogram highlights three years (1979, 1995, and 2001) with storm activity twice as great as the mean one. In the past 10 years, noticeable fluctuations in the storm activity index have been traced.

To estimate the extreme values of mean wave heights $\overline{h} = 0{,}63 \cdot h_S$ and mean wave periods $\overline{\tau}$ possible once every *n* years, the extreme Gumbel distribution [9, 11] obtained on the basis of a sequence of annual maxima and SWAN-ERA series was applied. Then, using the distribution functions of wave elements for the sea of finite height [2], which includes $\overline{h}$ and $\overline{\tau}$ maxima, the heights and periods of waves of different probability in the system of storms possible once in *n* years were determined.



F i g. 6. Yearly distribution of the storm power total index *SPI* normalized to its mean long-term value SPI_m (9 m depth)

The results of calculations of the waves' extreme characteristics are given in Table 1. It follows that for a storm of 4% regime probability (possible once every 25 years), the calculated value of the wave height of one percent probability is 5.3 m. This value, along with $\bar{\lambda}$ and $\bar{\tau}$ value, is required when designing coastal protection structures such as groins and breakwaters.

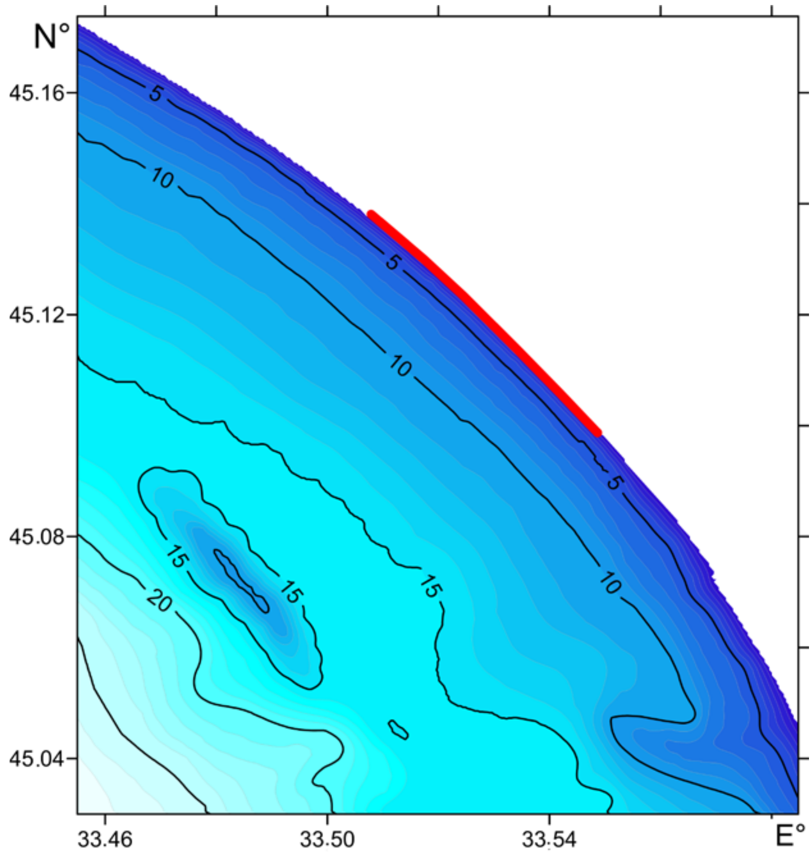
T a b l e 1

Significant wave height h_s, mean wave height $\bar{h}$, mean wave period $\bar{\tau}$, mean wave length $\bar{\lambda}$, wave height of the 13% -, 3% - and 1% probability in the system of storms which are possible once per 1, 5, 10, 25, 50 and 100 years (based on the SWAN-ERA data, 9 m depth)

T, years	Wave characteristics						
	h_S, m	$\bar{h}$, m	$\bar{\tau}$, s	$\bar{\lambda}$, m	$h_{13\%}$, m	$h_{3\%}$, m	$h_{1\%}$, m
1	3.4	2.0	9.2	83	3.1	3.8	4.3
5	3.7	2.3	10.2	94	3.5	4.3	4.7
10	3.7	2.5	10.8	100	3.7	4.5	5.0
25	4.0	2.6	11.5	107	3.9	4.8	5.3
50	4.0	2.8	12.0	112	4.1	5.0	5.5
100	4.2	2.9	12.5	118	4.2	5.1	5.7

Mathematical modeling results and their discussion

Now we are to consider the main features of the spatial structure of wave fields. The fields of wind waves in the area under study are determined by the velocity, direction, and time of the wind, the bottom relief features, the coastline configuration, as well as the values of effective fetches. The design area is characterized by a relatively straight coastline and isobaths parallel to it (Fig. 7). Thus, the wave fields in the coastal direction will be relatively homogeneous.



F i g. 7. Model bottom topography in the region of the Sakskoe Lake bay-bar. Red line shows the design area

The SWAN model and the 4-step nested grid method described above were used to model the wave fields. Calculations were made for a time period of 16 hours for a spatially homogeneous wind of 4% regime probability [3]. For all four calculated areas, the SWAN model angular resolution was 10º. According to the frequency coordinate, varying within the range of 0.04–2 Hz, an uneven grid

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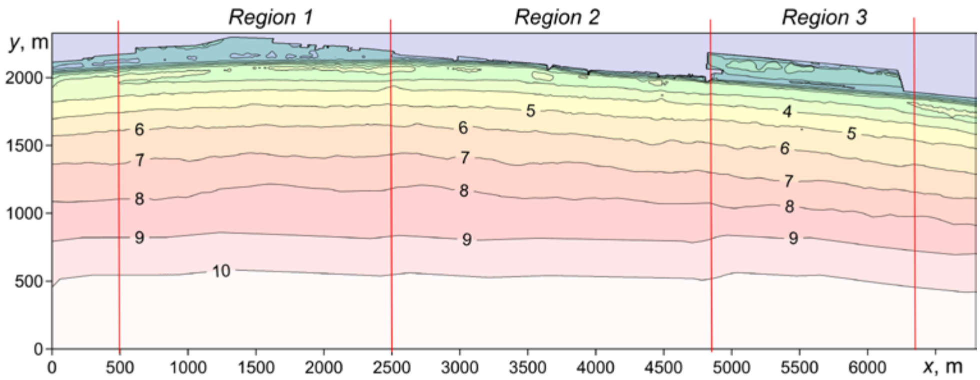
[3] Lopatukhin, L.I., Bukhanovskii, A.V., Ivanov, S.V. and Chernyshova, E.S., eds., 2006. *Reference Data on Wind and Waves Regime of the Baltic, Northern, Black, Azov and Mediterranean Seas*. St. Petersburg: Russian Maritime Register of Shipping, 450 p. Available at: https://ohranatruda.ru/upload/iblock/91f/4293747775.pdf [Accessed: 12 May 2022].

with 31 nodes was applied. In the fourth calculated area, the grid pitch was ~ 40 m. Time integration was carried out according to an implicit difference scheme with 30 min step.

As the simulation results show, the most intense waves occur at a southwesterly wind, which is due to maximum fetch. Due to the shallow water of the area under study, refraction has a significant effect on the waves. When approaching the shore, the wave fronts are oriented parallel to the isobars and the mean direction of the waves becomes perpendicular to the isobaths. At an isobath of 10 m, the values of mean wavelengths $\bar{\lambda}$ are within 70–105 m range, in the immediate vicinity of the shore they decrease to 45–55 m.

An important factor determining the wave energy loss due to bottom friction is the amplitude of the orbital velocity of wave motion at the bottom V_b [5]. The calculations revealed that near the shore (at 10 m depths or less), the characteristic values V_b are 1.1–1.4 m/s. The spatial distribution of the breaking zones enables us to judge the loss of wave energy due to the collapse of waves. In the SWAN model, the quantitative criterion of breaking is the proportion of breaking waves Q_b [5]. As was revealed by the analysis of the fields Q_b, in all the considered cases, the outer boundary of the wave breaking zone corresponds to ~ 4 m isobath.

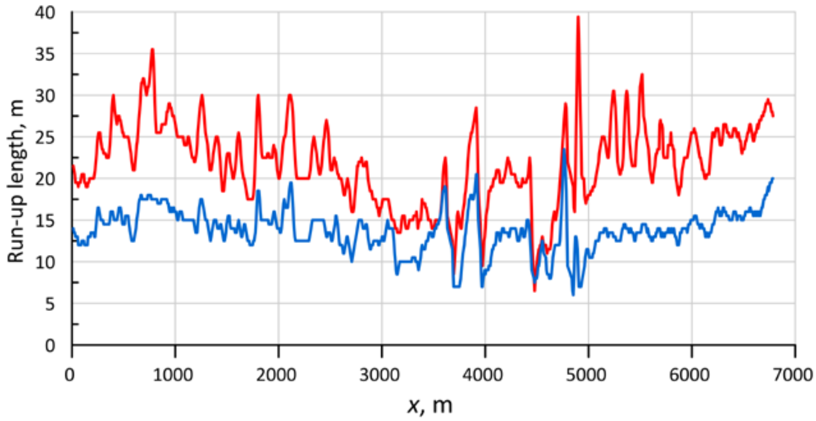


F i g. 8. Bottom and land relief (m) of the coastal zone for modeling the wave run-up on the coast and the beach profile deformations

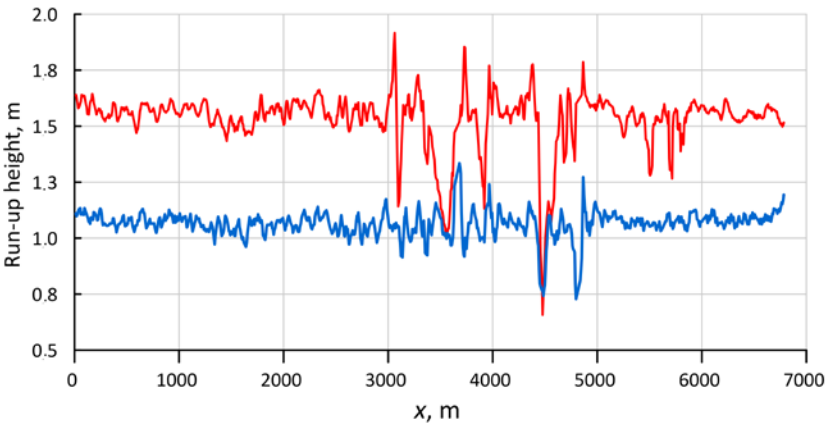
The SWASH model was applied to assess the characteristics of the wave run-up on the shore of the studied area. The bottom relief of the calculated area is shown in Fig. 8. The *x*-axis is oriented along the general direction of the coastline; the *y*-axis – in the direction perpendicular to the coastline general direction. A grid with 6.8 m step in *x* and 2.5 m in *y* was used. The time integration step was 0.02 s. At the seaward boundary ($y = 0$) of the computational domain the wave characteristics were determined on the basis of the JONSWAP spectrum [6] at h_S and τ_P corresponding to the storm of 4% regime probability. The radiation condition was set at the liquid lateral boundaries. The integration time was 360 s.

During the simulation, the maximum possible values of the run-up length and height were determined for each *x*.

Calculations of the maximum lengths and height of the waves run-up were performed with the hydrostatics condition (HM variant) and without this condition (NM variant). The simulation results are presented in Fig. 9 and 10. Red curves correspond to the non-hydrostatic version of the SWASH, the blue curves – to the hydrostatic one. As can be seen, the run-up length and height change significantly along the coastline due to the variability of the bottom slopes and the slopes of the beach surface part in different parts of the design area, as well as the presence of a seawall and other coast protection structures.



F i g. 9. Run-up maximum length along the coast of the area under study for a storm of the 4% regime probability. Red curve is a non-hydrostatic model, blue curve is a hydrostatic one



F i g. 10. Run-up maximum height along the coast of the area under study for a storm of the 4% regime probability. Red curve is a non-hydrostatic model, blue curve is a hydrostatic one

A comparison of the HM and NM variants revealed (Table 2) that in comparison with the hydrostatic model, the non-hydrostatic one gives, on average, a higher run-up length (by 37%) and height (by 27%).

T a b l e 2

Statistical characteristics of the maximum wave run-up along the coast in the system of a storm of the 4% regime probability (HM – hydrostatic model, NM – non-hydrostatic model)

Value	Statistical characteristics			
	Maximum wave run-up length, m		Maximum wave run-up height, m	
	HM	NM	HM	NM
Maximum	25.0	41.5	1.8	2.0
Minimum	2.5	2.5	0.2	0.5
Mean	13.8	21.9	1.1	1.5
Median	15.0	22.5	1.1	1.6
Standard deviation	2.9	5.1	0.1	0.2

Further the modeling of the coastal zone profile deformations for storms of different duration was carried out. Since the bottom relief in the area under study is quite homogeneous in the coastal direction, the coastal zone transverse profiles averaged for three regions were used (the boundaries and region numbers are given in Fig. 8).

Storm surge at the computational domain seaward boundary was set using the JONSWAP spectrum. The calculated grid had 2.3 m step; the storm duration was 12 hours.

During the modeling, the width of the coast erosion zone (L_C) and the length of the bottom deformation zone from the water edge to the sea (L_S) were calculated. The starting point for determining the L_C and L_S parameters was the position of the water edge at the initial moment of time. The bottom deformation zone outer boundary was determined by the coordinate of the first seaward point, in which the bottom deformations exceeded 0.1 m in absolute magnitude. Calculations were carried out for two fractions of bottom sediments [12]: fraction *1* – medium-sized sand (D_{50} = 0.375 mm), fraction *2* – fine gravel and coarse sand (D_{50} = 0.8 mm).

The results of L_C and L_S calculations for different storm durations are given in Tables 3 and 4. It can be seen that the greatest changes in these parameters occur within the time interval of 6 hours. For fraction *2*, the width of the coastal erosion zone is 2.5–3.5 m less than for fraction *1*. The smallest coastal erosion occurs in the southern part (region *3*). At a storm duration of 12 hours, the following estimates of the mean values of the deformation parameters were obtained: $L_C = 19.1 \pm 2.2$ m, $L_S = 56.0 \pm 8.9$ m.

Table 3

Width of the coast erosion zone L_C (m) at different storm durations

Region	Fraction	Storm duration			
		3 hr	6 hr	9 hr	12 hr
1	*1*	4.0	14.4	18.1	20.3
	2	3.4	12.3	16.1	18.3
2	*1*	4.0	15.0	17.7	22.5
	2	3.4	12.8	15.3	17.0
3	*1*	4.2	13.6	17.5	19.8
	2	3.0	11.2	14.3	16.7

Table 4

Length of the bottom deformations zone L_S (m) from the water edge at different storm durations

Region	Fraction	Storm duration			
		3 hr	6 hr	9 hr	12 hr
1	*1*	18.6	39.2	46.1	53.0
	2	16.2	32.3	39.2	43.8
2	*1*	22.0	49.6	56.5	63.4
	2	19.7	40.4	47.3	54.2
3	*1*	18.9	49.8	62.6	69.5
	2	16.6	39.6	51.1	58.0

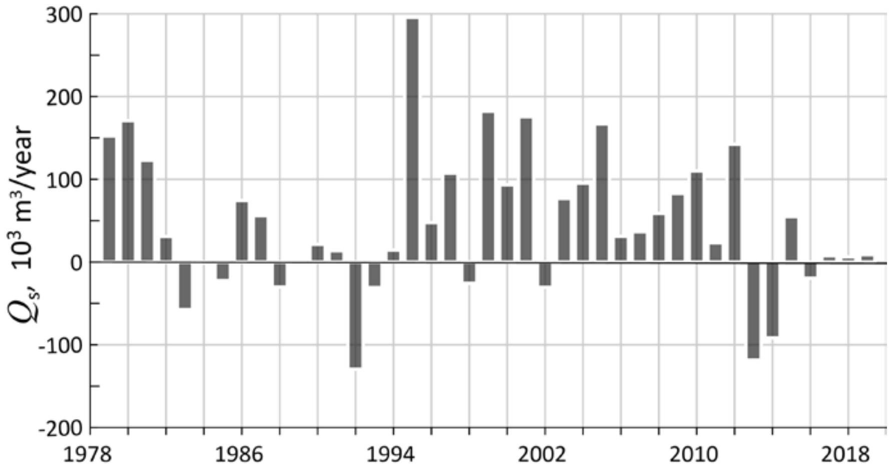
The above-mentioned consistency of the assumption about the convergence of sediment flows and a balance close to zero (which was the basis of the design decisions) was also analyzed. For these purposes, based on the data of retrospective calculations of the waves and the CERC formula [13], the values of the total annual long-range sediment flow at the design site for 1979–2019 period were obtained.

The CERC formula used a composite array of storm surge parameters obtained from SWAN-ERA data for 1979–2019 period. Only storm waves (h_S > 1.54 m) directed towards the shore were included in the array. That is, the mean direction of the waves θ satisfied the condition $|\theta_N - \theta| < 90°$, where θ_N = 232 ° is the angle corresponding to the direction of the external normal to the general coastline direction of the area under study θ_C = 142 °. The analysis revealed that in 80% of cases storm waves approach the coast from the southwest (225°) and in the remaining 20% – from the west-southwest. The largest number of strong storms corresponds to the southwestern direction.

As demonstrated above, in the area under study wave breaking begins from the depth H_C = 4 m. Therefore, in the CERC formula, the wave height in the breaking zone h_{SC} was estimated by the expression $h_{SC} = \min(\gamma H_C, h_S)$, where γ = 0.73 is the breaking index.

The results of calculating the total along-shore flows are given in Fig. 11. The mean annual value Q_S is 61,000 m^3/year, while in 71% of cases the sediment flow is directed counterclockwise towards Evpatoriya. Statistical characteristics are the following: the maximum is 391,000 m^3/year, the minimum is 174,000 m^3/year, the median is 39,000 m^3/year, the standard deviation is 115,000 m^3/year.

The values of the flows closest to the mean were observed in 1987, 1996, 2007, 2008, and 2015. Over the past several years (2015–2019), the calculated values Q_S were small, i.e. during this period, the positive and negative total sediment flows compensated for each other within the year.



F i g. 11. Distribution of the total along-coastal sediment flow Q_s by the years. At $Q_s > 0$, it is directed from the southeast to the northwest, at $Q_s < 0$ – from the northwest to the southeast

It should be noted that due to the lack of data on direct observations of flows in the area under study, the estimates of Q_S obtained above provide only a qualitative (balance) picture of the long-range sediment flow interannual variability.

Based on the GenCade integral model, estimates of shoreline changes for 5 variants of coast protection structures, including the variant embodied in the project, were obtained. The grid step along the coastal coordinate was 20 m, the integration step in time was 15 min. Two values of the mean diameter of particles D_{50} (0.4 and 2.0 mm) were used. At the model input, an array of SWAN-ERA wave parameters was set (height, direction and storm wave period with 1-hour step). The modeling was carried out for one-year time interval.

Calculations were performed for three years with different values of the total along-coast sediment flow Q_S: for 2015 (the flow is close to the mean long-term value), for 1995 (pronounced flow in the north-western direction) and for 1992 (pronounced flow in the south-eastern direction).

It was found that from the point of view of minimizing the coastline changes, the option with 10 short groins is the most preferable, while the annual changes in the water edge position do not exceed ±20 m. For the variant embodied in the project, the simulation results revealed significant changes in the water edge position within the central section, in the area of intermittent breakwaters, with a possible significant reduction in the beach width in the areas not covered by the breakwaters.

These conclusions clearly confirm the actual changes in the coastal strip position. The construction of a transverse structure (the length of which along the normal to the shore is about the same as the projected groins) led to a reduction in the width of the beaches on the site with a total length of ~ 10 km. At the same time, in some areas the shore retreat reached up to 40 m.

Conclusion

Based on the studies performed, it can be concluded that the design consideration, if implemented completely, can significantly disrupt the existing natural system of coastal zone formation, which will lead to significant negative consequences for the coast in the area of up to 10 km. These consequences can be expressed in reducing the width of the beach area, lowering the beach height, replacing the sandy beach with a pebble-gravel one in some areas. Taking into account the planned location of the embankment under construction and the marking of the enclosing wall foundation in some areas, a wash-away and damage to the embankment wall is possible. According to our estimates, the implementation of the project in its current form will inevitably lead to the need to carry out the work on the installation of coast protection structures in addition to another section with a length of more than 10 km. It is appropriate to note here that these conclusions have been confirmed in practice: even partially constructed coast protection structures in the winter storm period of 2021–2022 had the negative impact we predicted on the coastal zone. Due to this, the adoption of urgent emergency measures was required.

According to the results of the work carried out, we have made recommendations to exclude project structures (125 m long groins, intermittent underwater breakwaters), the existence of which will significantly affect the along-coast sediment flow and will further lead to the shore degradation in adjacent areas. Based on the recommendations, a new project was developed.

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Yuri N. Goryachkin – problem statement, lithodynamics retrospective analysis, preparation of the paper

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.